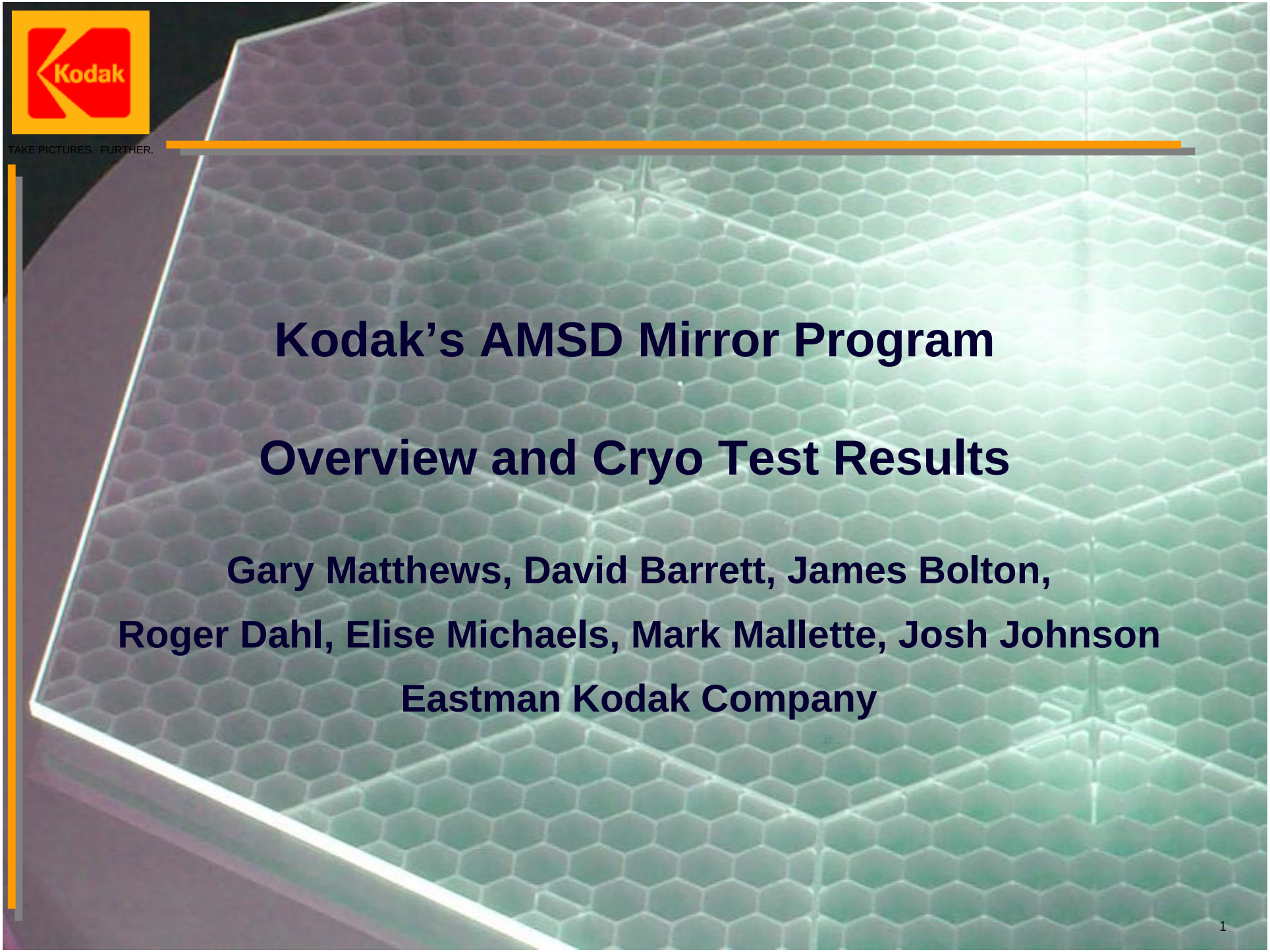


Kodak's AMSD Mirror Program

Overview and Cryo Test Results

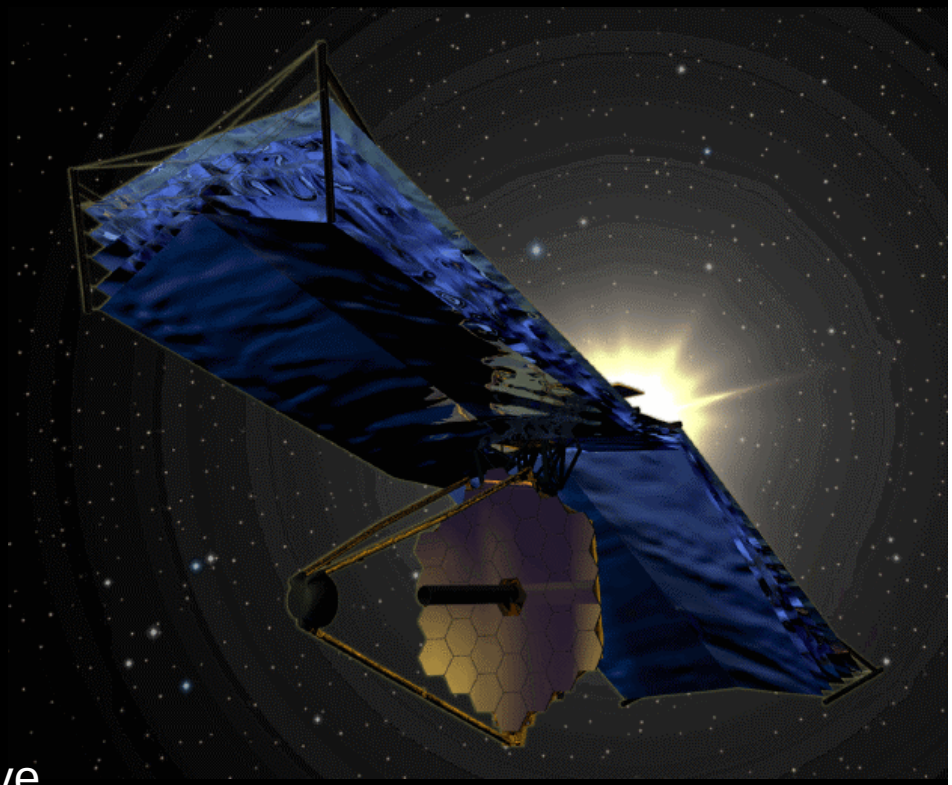
Gary Matthews, David Barrett, James Bolton,

Roger Dahl, Elise Michaels, Mark Mallette, Josh Johnson

Eastman Kodak Company

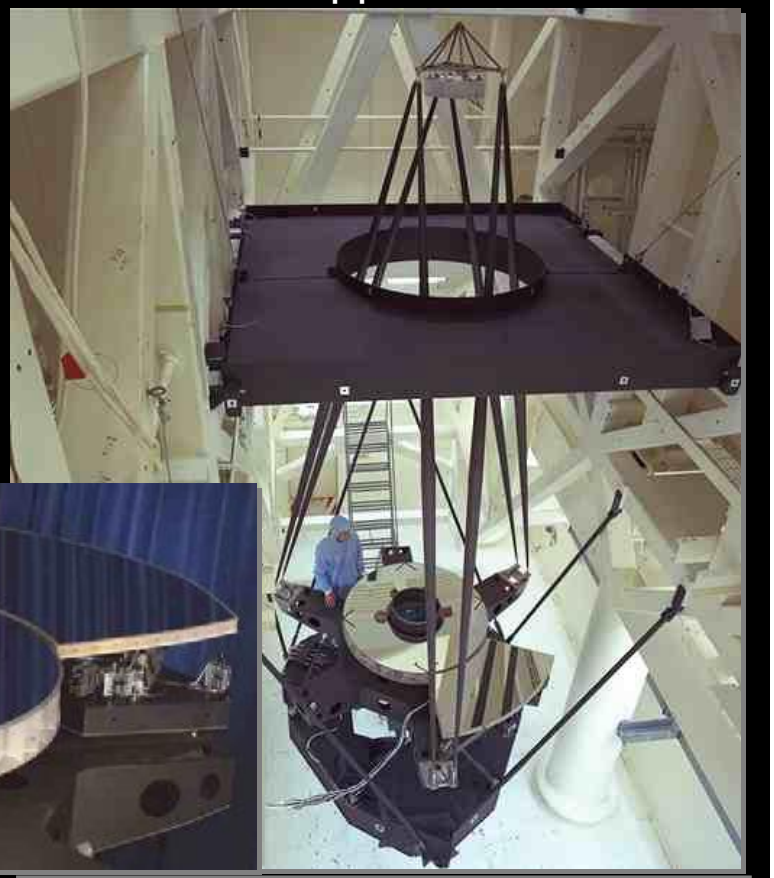
Next Generation Optical Systems

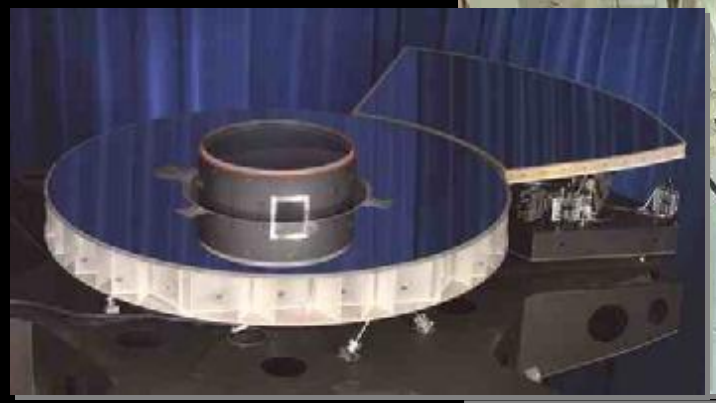
- **Next generation optical systems will need ultra-lightweight adaptive optics**
  - James Webb Space Telescope (JWST)
  - Space Based Laser (SBL)
  - Terrestrial Planet Finder (TPF)
- **Advanced Mirror Systems Demonstrator (AMSD) addresses these needs**
  - Provides ultra-lightweight adaptive mirror technology and manufacturing assessment



Semi-Rigid Mirror Approach

- **Kodak's concept for active mirror technology**
  - Ultra-lightweight semi-rigid cored mirror with sparse force actuators
  - Very different than high density, displacement actuator approach
- **Kodak built and demonstrated semi-rigid approach in 1989 on a 2.5 meter testbed**
- **The AMSD joint venture allows concept to be updated using latest technology**



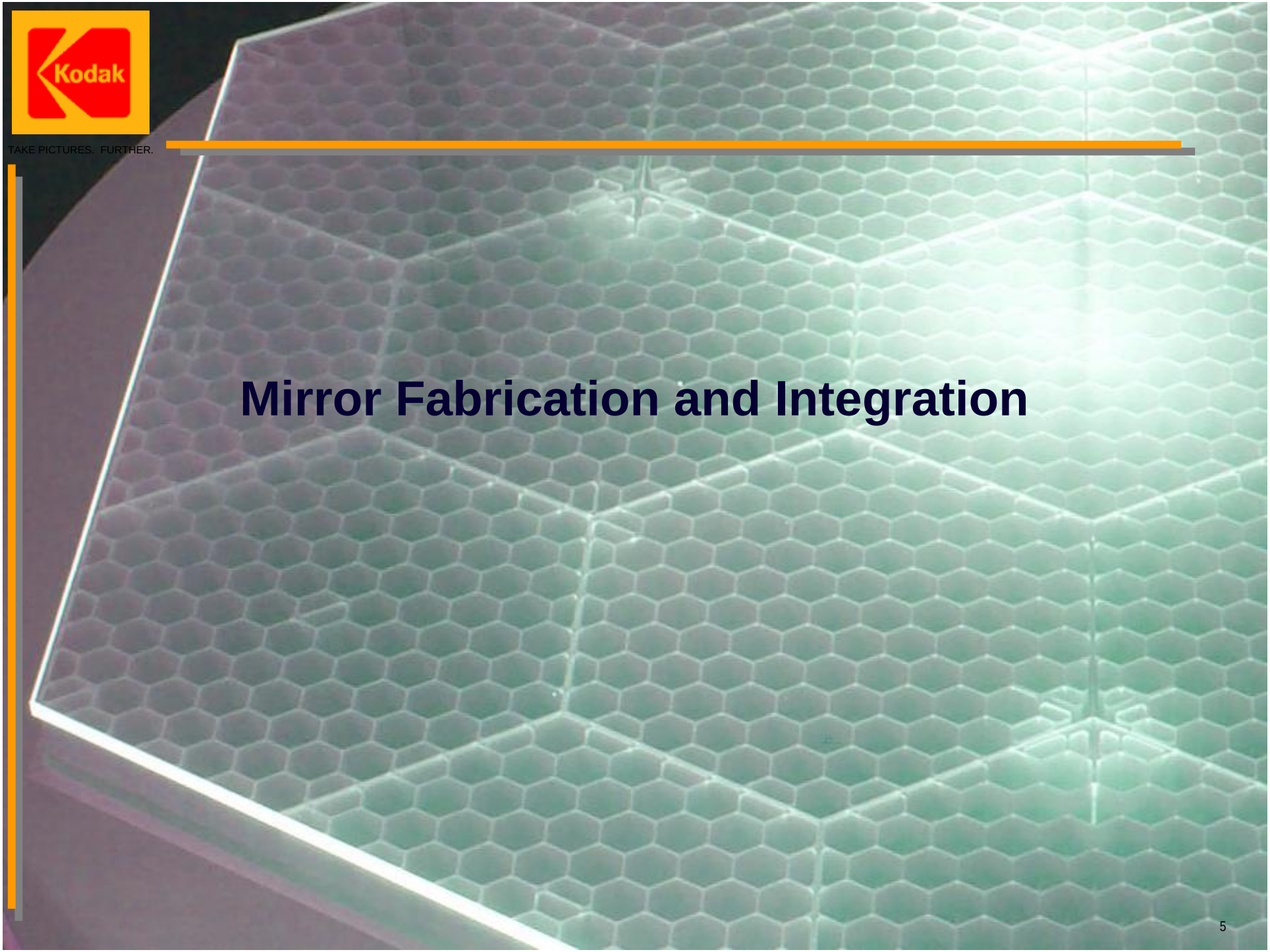


System phase and figure control to visible tolerances over long periods of time completed

TAKE PICTURES. FURTHER.

Program History

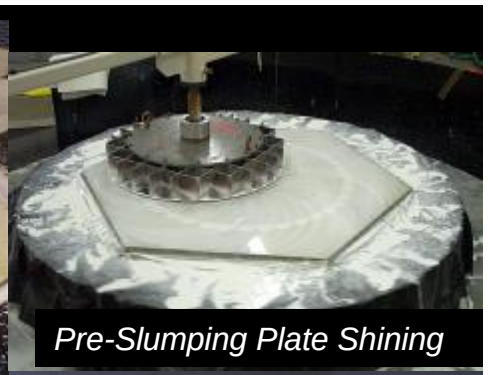
- **AMSD ULE® mirror design baseline (circa 1999)**
  - Medium authority mirror with 16 figure control force actuators
  - Optimized for warm applications
  - Not in any baseline for NGST (JWST)
  - ULE® has never been used for cryo applications
- **NGST/Ball/Kodak down selection for JWST changed everything**
  - Kodak AMSD ULE® mirror considered a viable back-up for beryllium low authority mirror baseline
  - AMSD baseline medium authority design did not meet JWST figure control architecture
- **JWST team posed the question**
  - How can we learn the most about how a ULE® mirror will work at cryo temperatures?
  - Kodak recommended eliminating the integration of the actuators and to test a “bare mirror” without actuators
    - Provides best insight into how a ULE® mirror would perform under cryo conditions
    - Radius of curvature control would be independent of material choice (Beryllium or ULE®)
    - With government concurrence, Kodak changed the integration plan and cryo testing in order to understand the applicability of a ULE® glass mirror for JWST cryo application



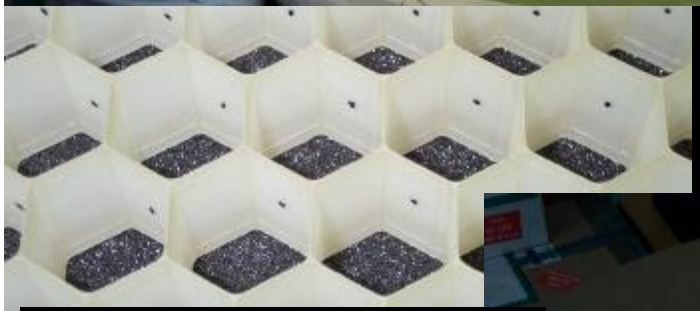
Mirror Fabrication and Integration

Mirror Assembly

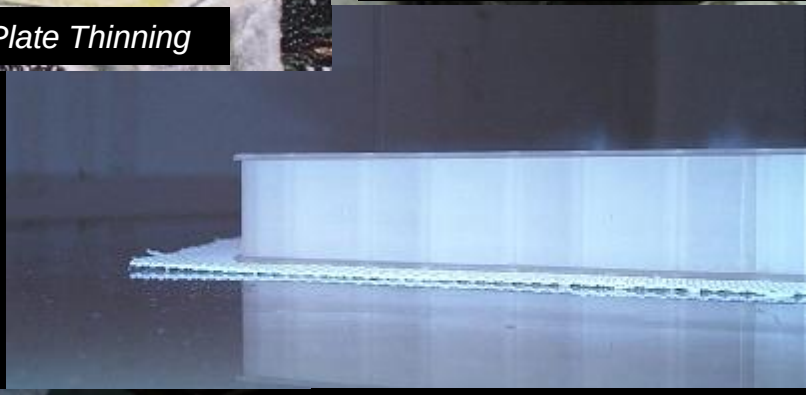
Pre-Slumping Plate Thinning



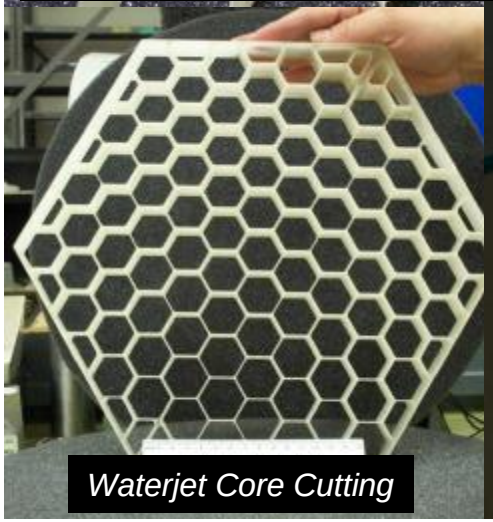
Pre-Slumping Plate Shining



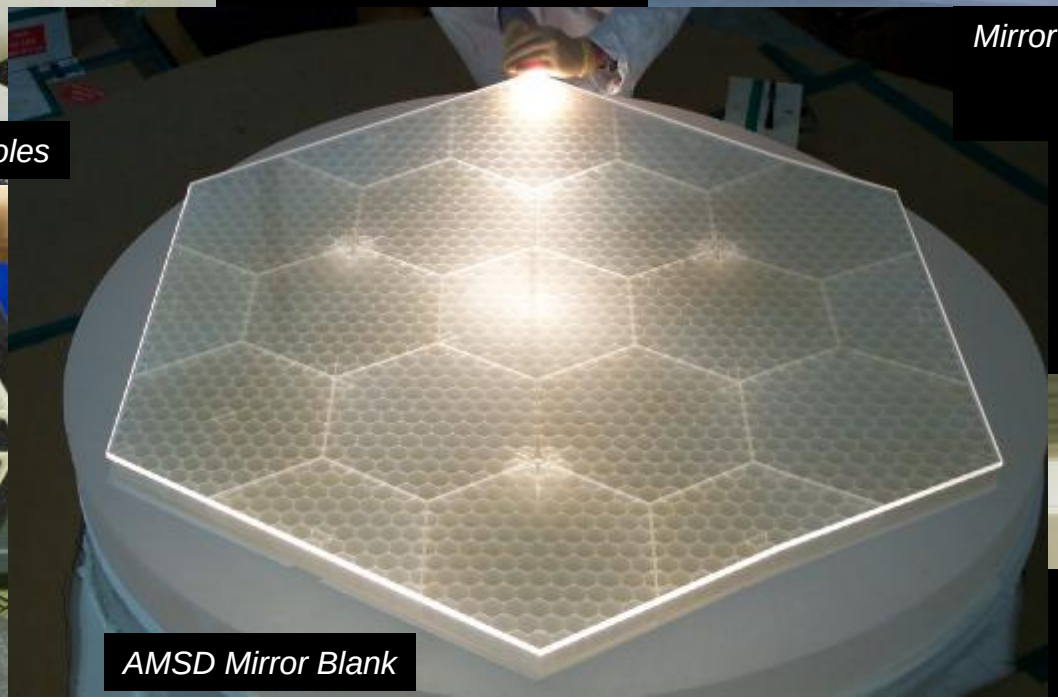
Waterjet Cut Core with Vent Holes



Mirror Blank Ready for Slumping

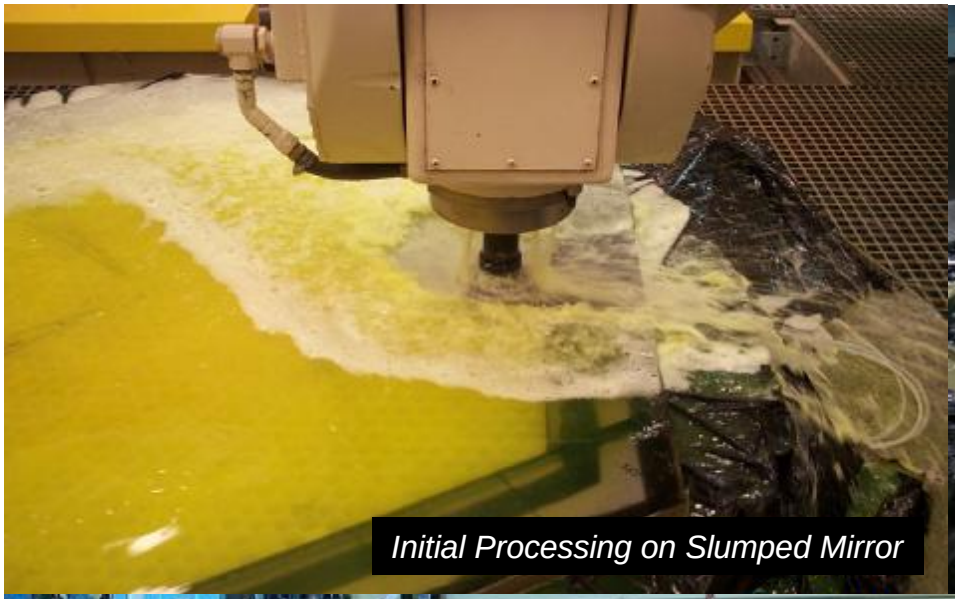


Waterjet Core Cutting



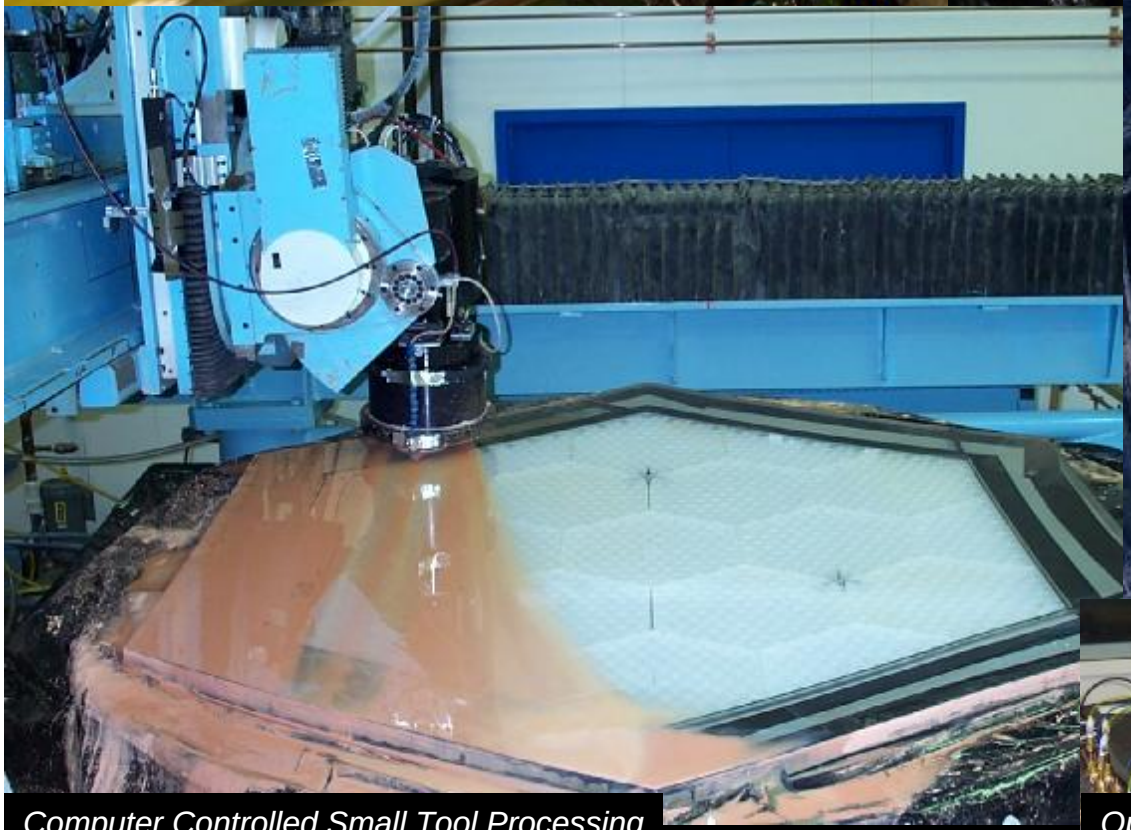
AMSD Mirror Blank

Slumped Blank Over Aspheric Mandrel to Near Net Shape

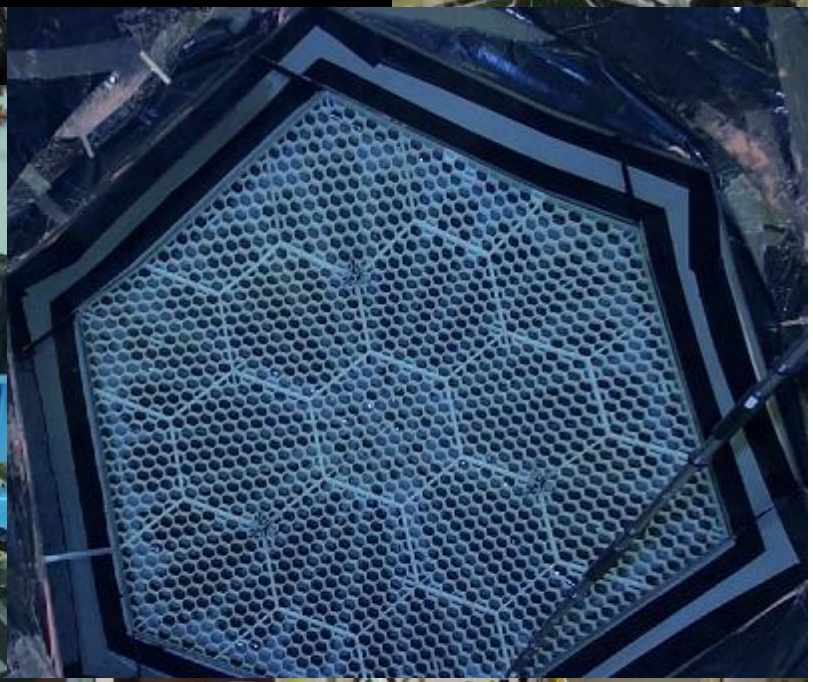


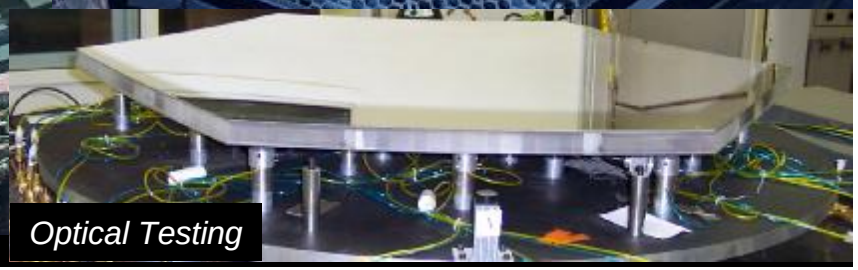
Initial Processing on Slumped Mirror

Final Aspheric Surface Generation

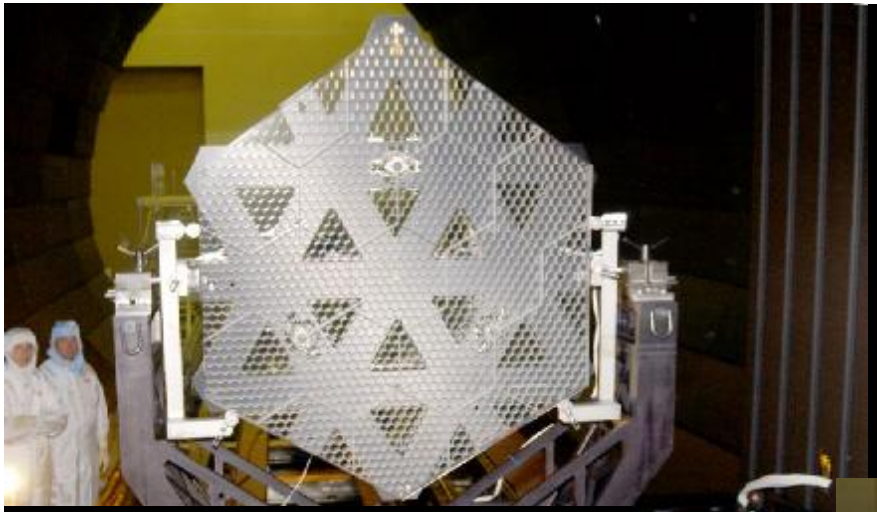


Computer Controlled Small Tool Processing



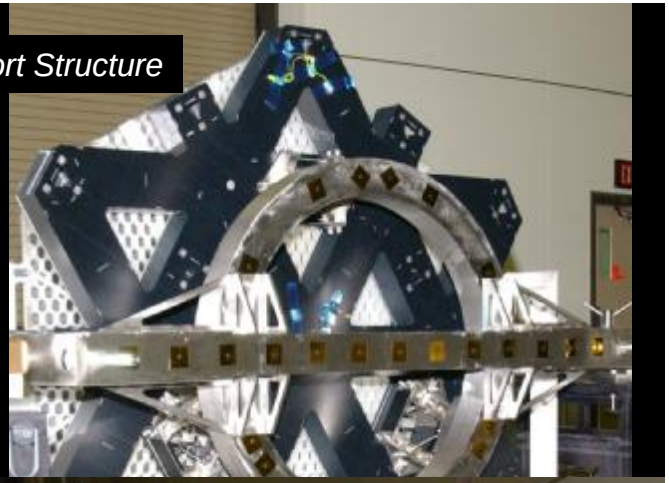


Optical Testing

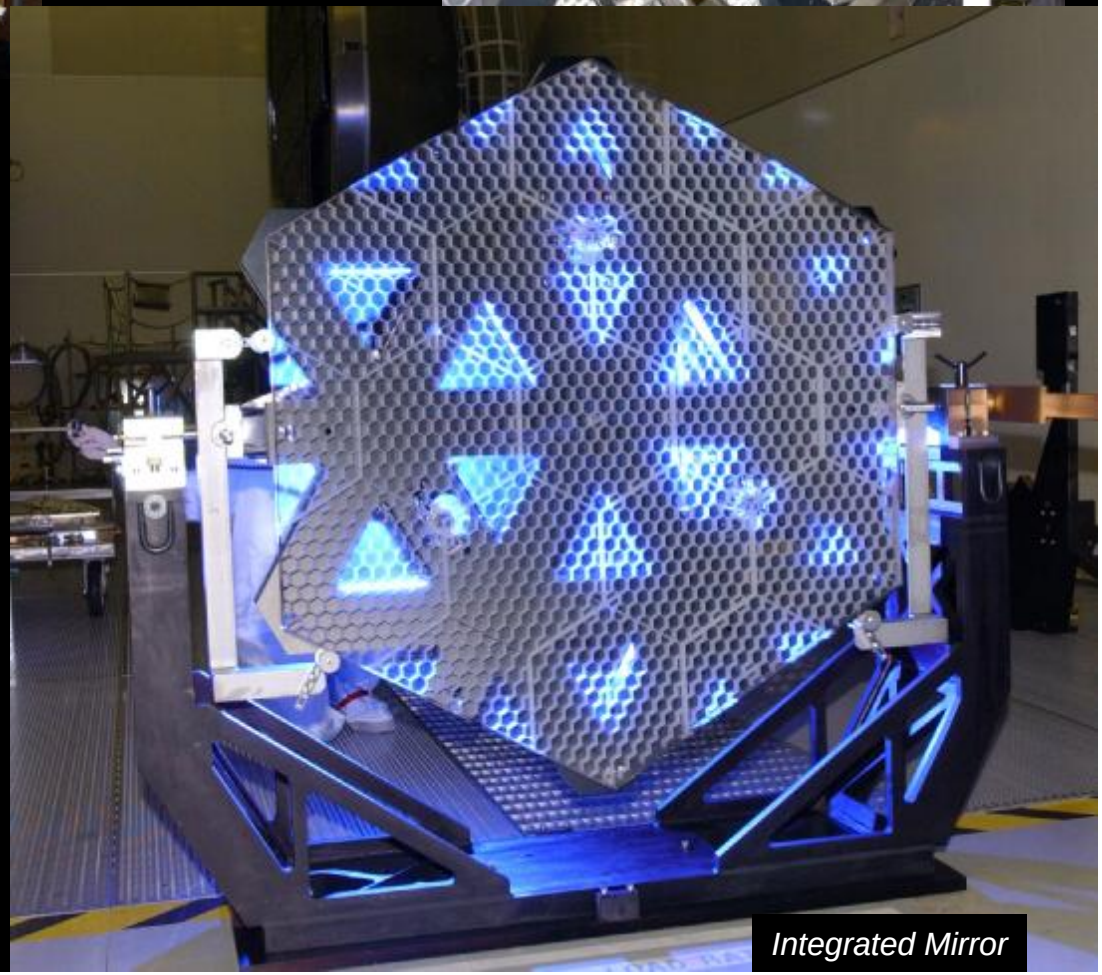


Integrated Mirror Ready for Test at MSFC

Mirror Support Structure

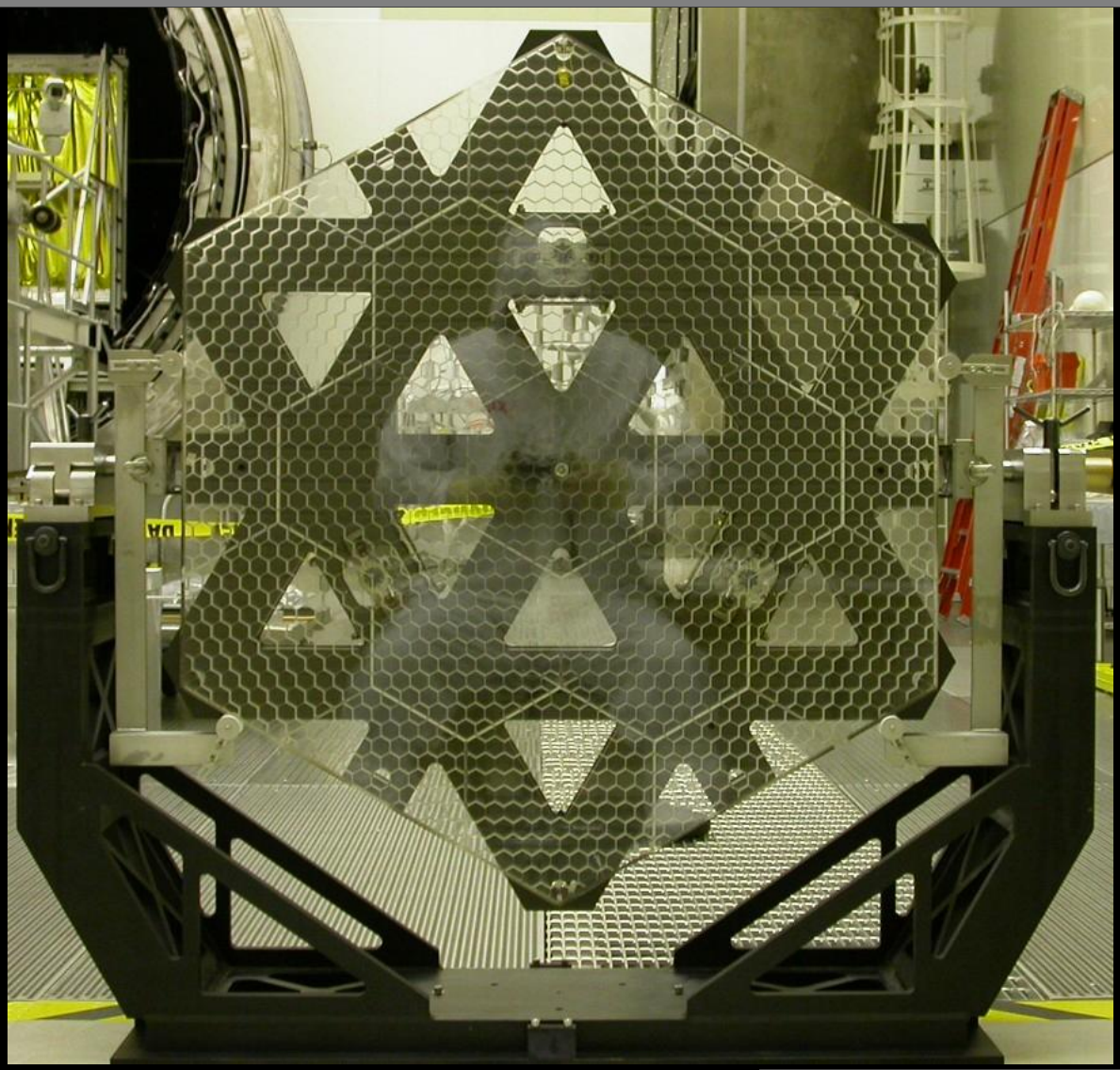


Final Mirror Inspection



Integrated Mirror

Cryo Test Configuration



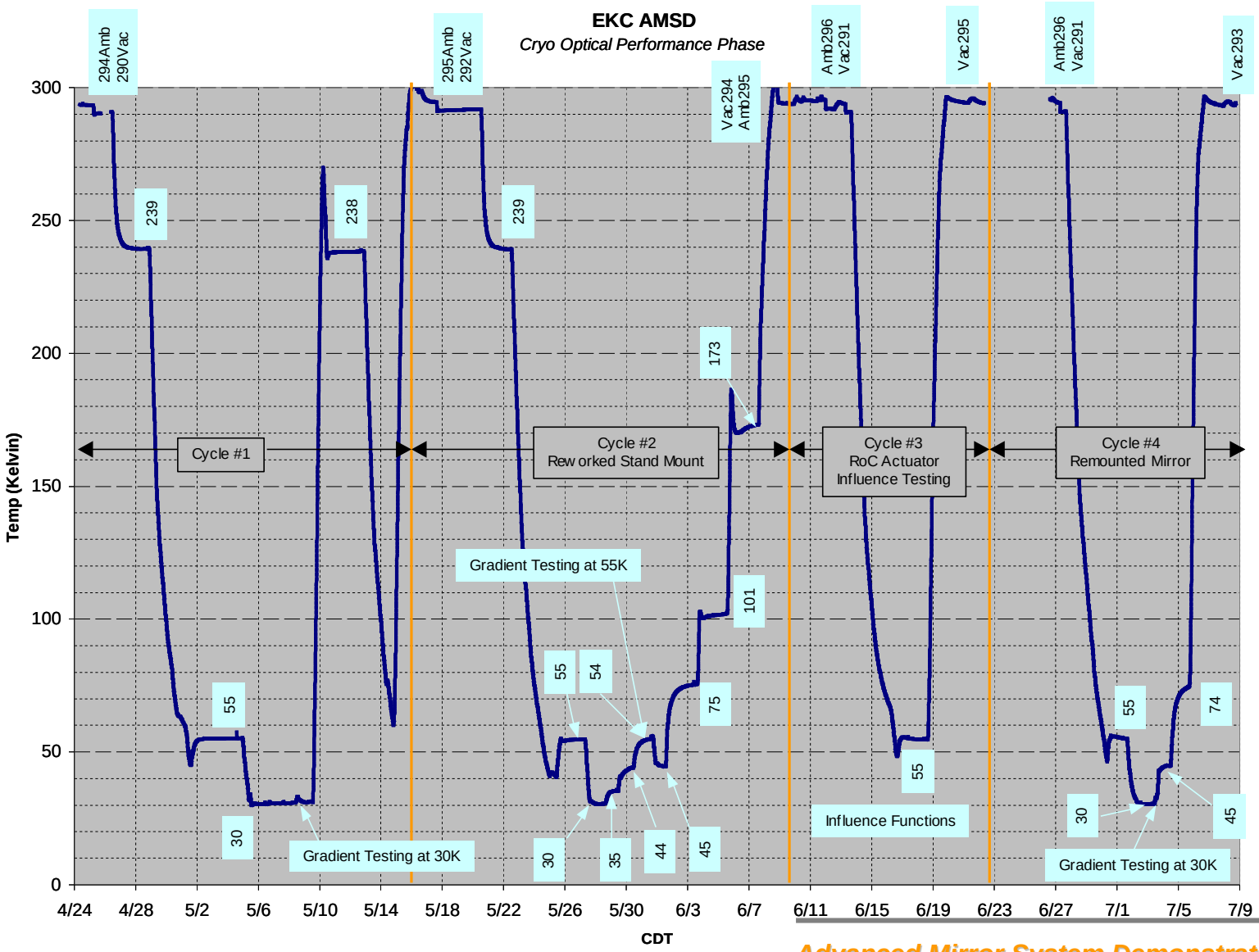
TAKE PICTURES. FURTHER.

Key Cryo Test Data Requirements

- **Will a large ULE mirror survive a 25°K environment?**
- **What is the mirror's figure change during cool down from 290°K to 55°K?**
  - Is this change repeatable
  - Drives Kodak's ability to cryo figure the JWST mirrors
- **What is the mirror's figure change over the operational temperature range of 55°K to 30°K?**
  - Is this change repeatable
  - Based on AMSD, can the wavefront and PSD requirements be met for a cryo figured mirror

TAKE PICTURES. FURTHER.

AMSD-II Cryo Test Cycles



TAKE PICTURES. FURTHER.

Cryo Survivability

- Mirror has successfully been through a 25K thermal soak
- Mirror has been through four additional cryo cycles to at least 50K
- No damage or degradation identified under careful inspection process by both Kodak and NASA personnel

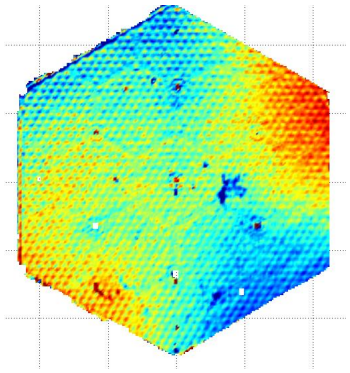
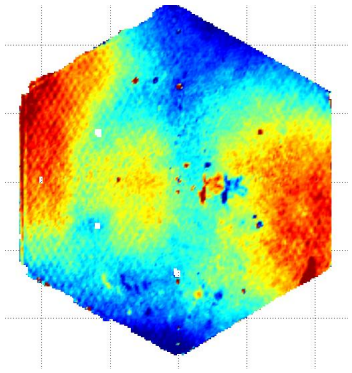
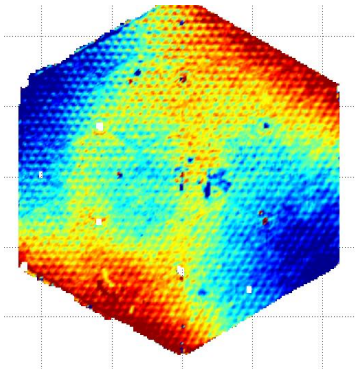
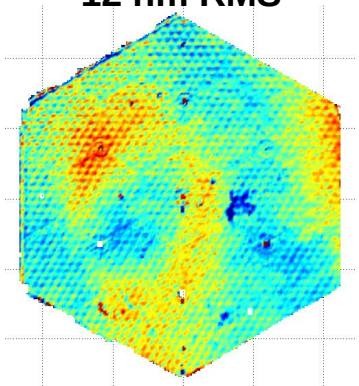
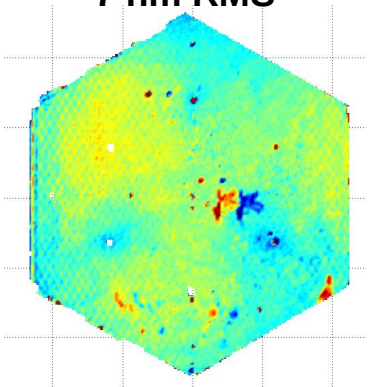
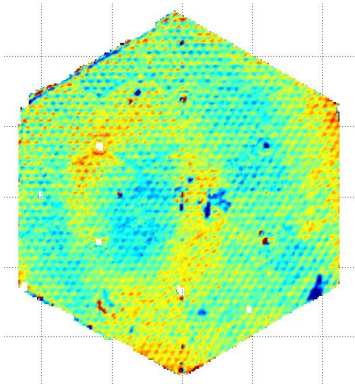
TAKE PICTURES. FURTHER.

Metrology Repeatability

- **Based on test results, determine the optical test repeatability**
  - Use difference maps to evaluate changes
  - Negates impact of gravity backout errors
- **Use near ambient data since environmental influences are negligible for the ULE® material**
- **Data will determine the error bars that need to be used when evaluating cryo test data**
  - Test uncertainty is about 46nm RMS

TAKE PICTURES. FURTHER.

Test Reproducibility at Ambient (First and Second Cycles)

	Vacuum/238 – Vacuum/239	Vacuum/238 – Vacuum/239II	Vacuum/239II – Vacuum/239
Raw Data			
	16 nm RMS	20 nm RMS	23 nm RMS
SHM Data	12 nm RMS 	7 nm RMS 	10 nm RMS 
	X: 0.0, Y: 0.01	X: 0.01, Y: 0.16	X: -0.01, Y: -0.16

Difference in hexapod position between data sets (mm)
SHM – Data after simulated hexapod motion

Temperature gradient effects not backed out

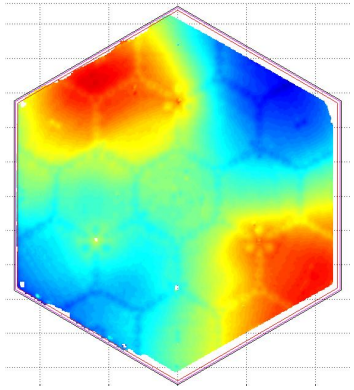
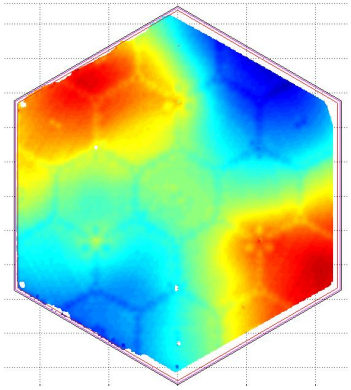
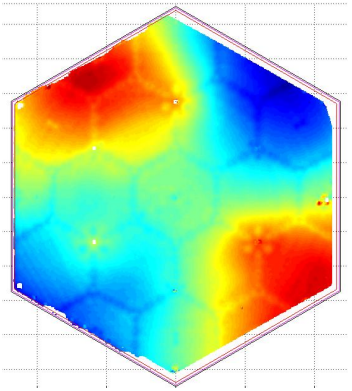
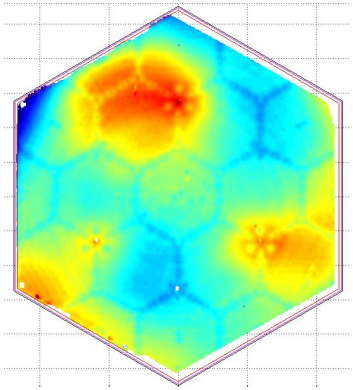
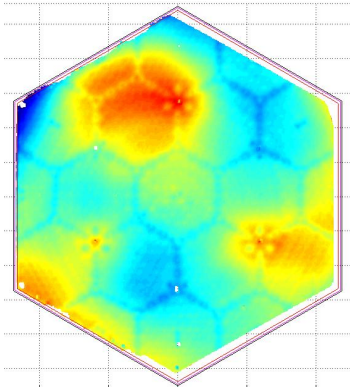
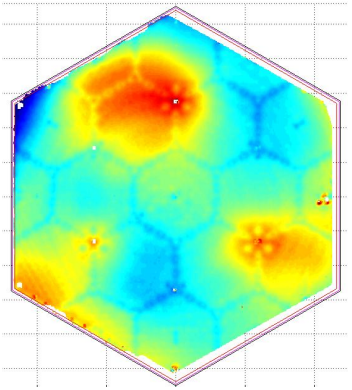
TAKE PICTURES. FURTHER.

Ambient to Cryo Figure Change

- **Ambient to cryo shift**
  - Approximately 400nm (0.63λ) RMS of surface change on the mirror
    - Larger than expected and driven by astigmatism
- **Repeatability**
  - Mirror figure is repeatable to within the accuracy of the current metrology
- **Ion Figurable**
  - Requirement is for a 20nm mirror at cryo temperature
    - PSD requirement for mid-spatials
  - Low order is easily correctable
  - Higher order PSD requirement will be difficult
    - Skeletonized effect due to core structure
    - Analysis and demonstration in work

TAKE PICTURES. FURTHER.

Ambient to Cryo Surface Figure Shift

	Cycle 2 Vac/55 – Vac/292	Cycle 3 Vac/55 – Vac/291	Cycle 4 Vac/55 – Vac/293
Raw Data			
	369nm RMS	394nm RMS	415nm RMS
SHM Data	168nm RMS 	164nm RMS 	171nm RMS 
	X: 0.0, Y: 2.84	X: -0.81, Y: 3.17	X: 0.0, Y: 3.22

Difference in hexapod position between data sets (mm)
SHM – Data after simulated hexapod motion

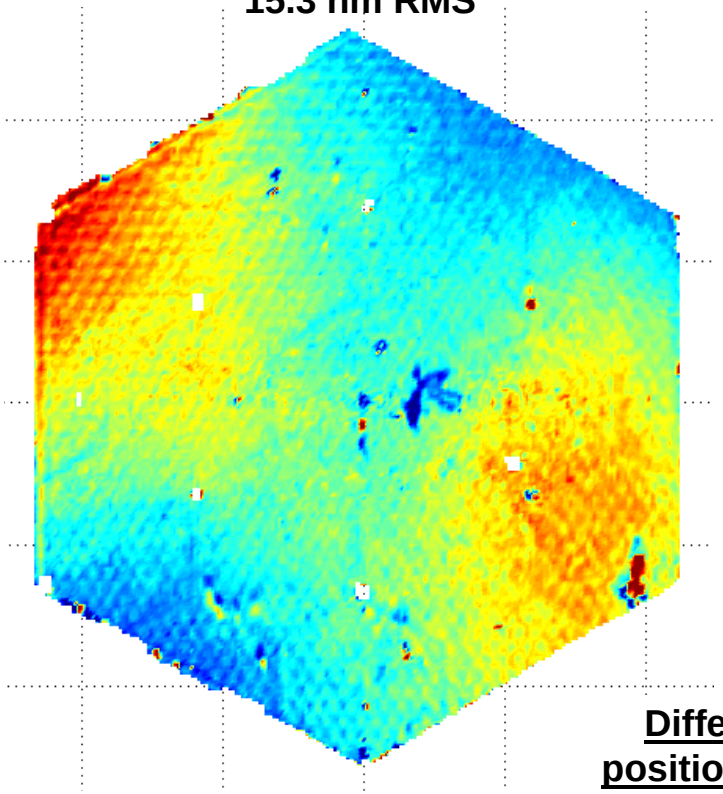
Temperature gradient effects not backed out

TAKE PICTURES. FURTHER.

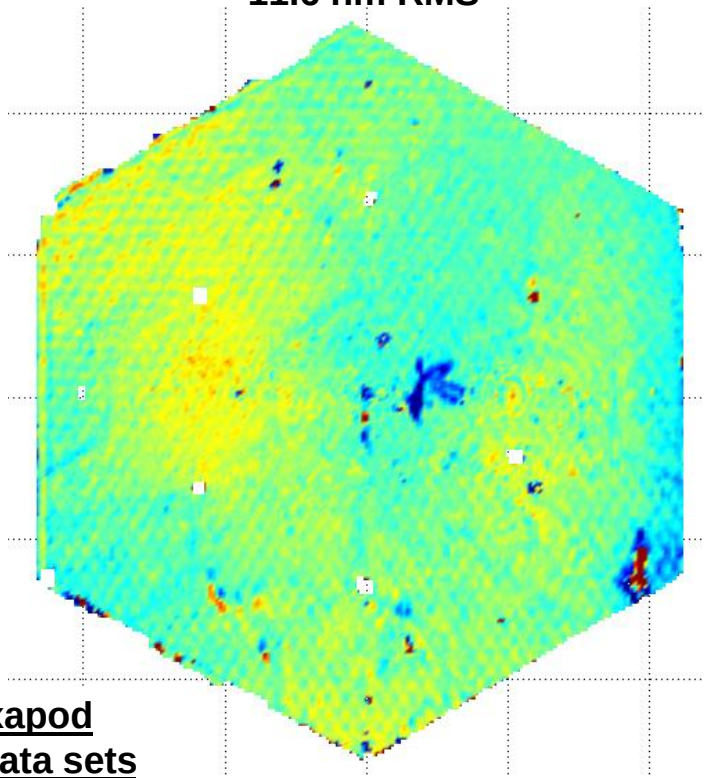
Cryo Surface Repeatability

Vacuum/30II – Vacuum/30
(Second Cycle - First Cycle)

Raw Data
15.3 nm RMS



After Simulated Hexapod Motion
11.6 nm RMS



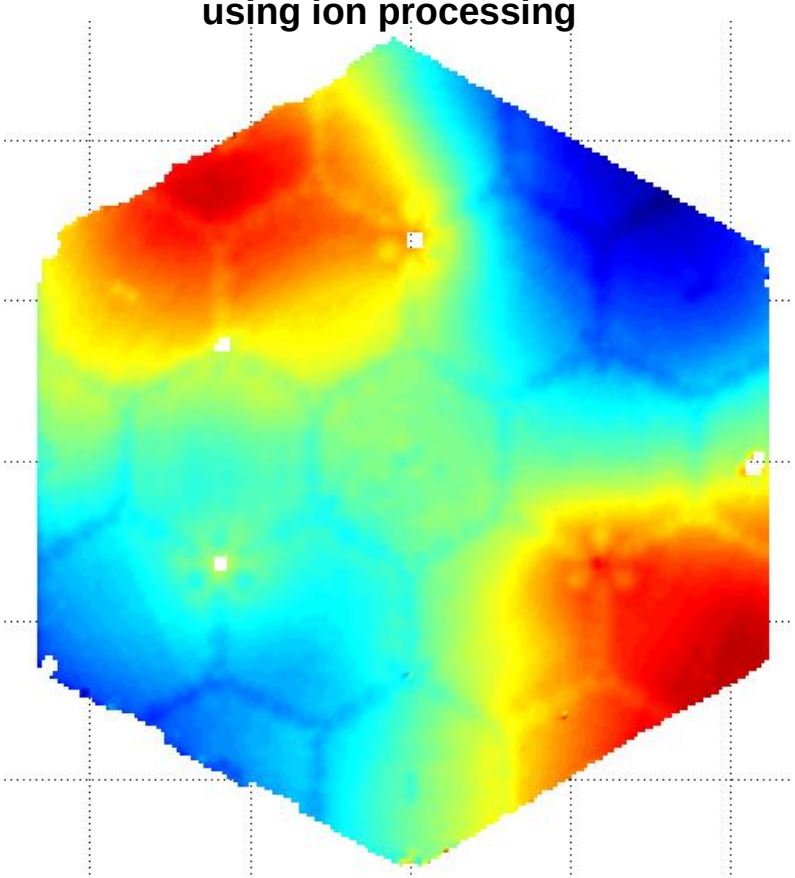
<u>Difference in hexapod position between data sets (mm):</u>
X: 0.0
Y: 0.07

Temperature gradient effects not backed out

TAKE PICTURES. FURTHER.

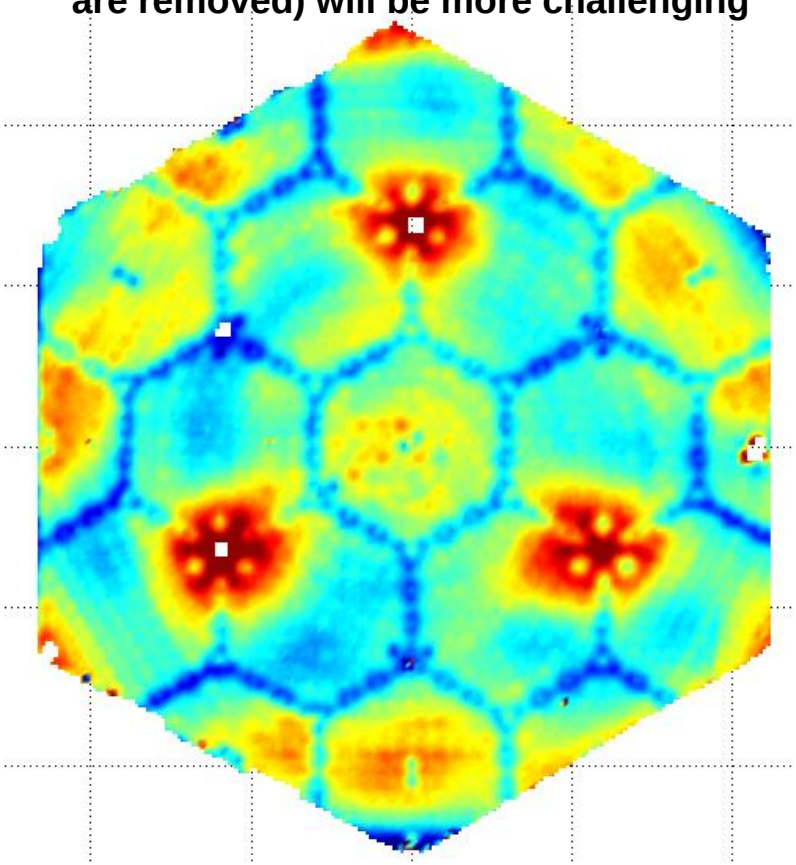
Ion Figuring Data

Global Figure Error is easily correctable using ion processing



413 nm RMS

Residual Error (after Zernike Polynomials are removed) will be more challenging

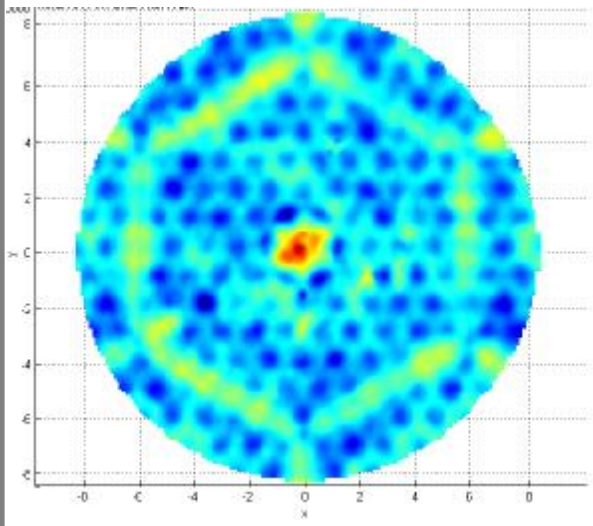


57 nm RMS

TAKE PICTURES. FURTHER.

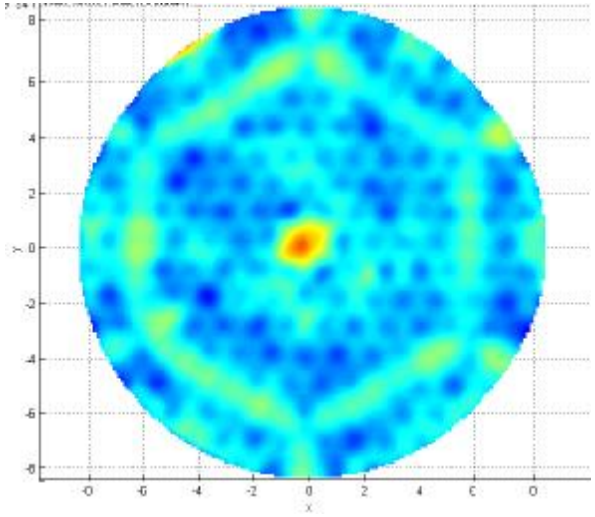
Correction of High Spatial Frequency Error

- 0.43m (17”) diameter plano generated to demonstrate Kodak’s ability to remove cryo-induced quilting using ion figuring system
- Hit map generated from test data
- Process shows good convergence towards the desired surface



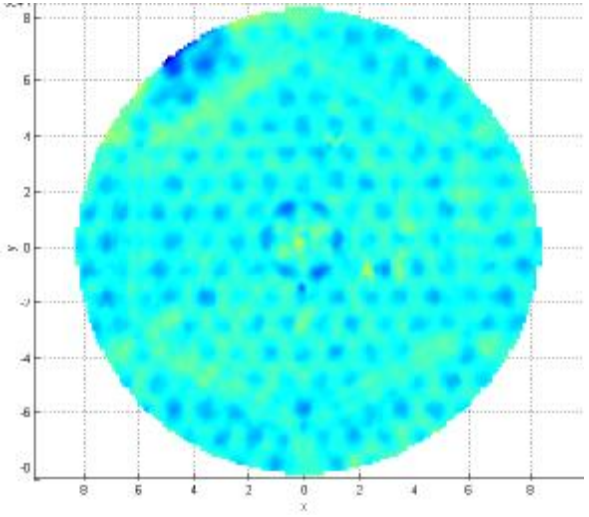
Desired Surface

RMS = 40nm



After ion

RMS = 31nm



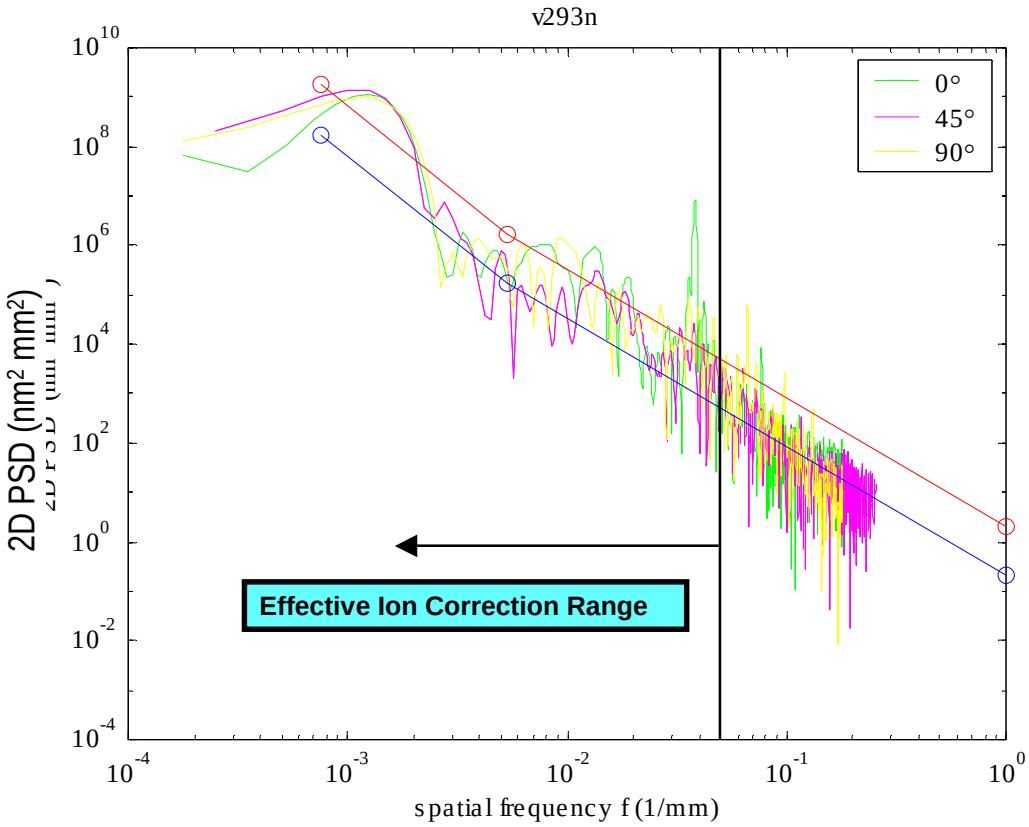
Delta

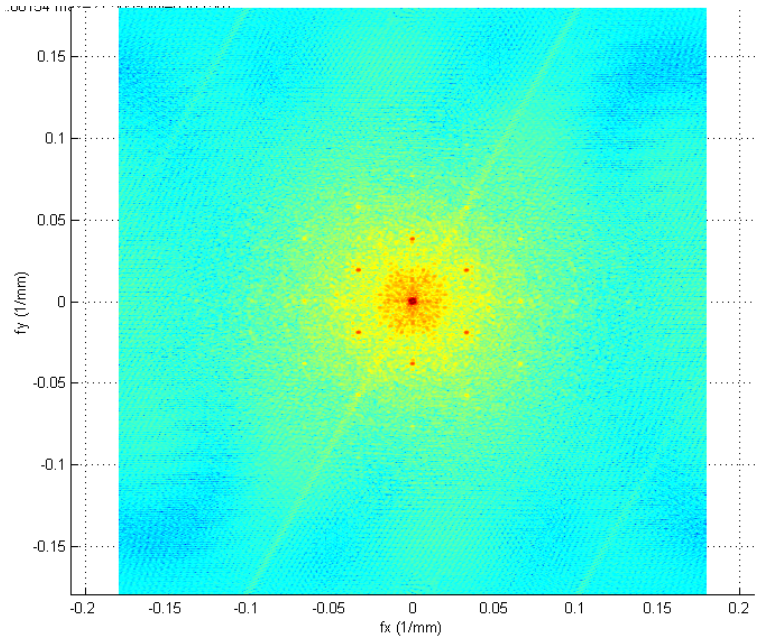
RMS = 17nm

TAKE PICTURES. FURTHER.

PSD Performance

- **Showing vacuum/293K AMSD data to JWST spec**
- **Did not attempt to correct quilting during processing**
  - Processes are now capable of reducing the quilting to near negligible levels





TAKE PICTURES. FURTHER.

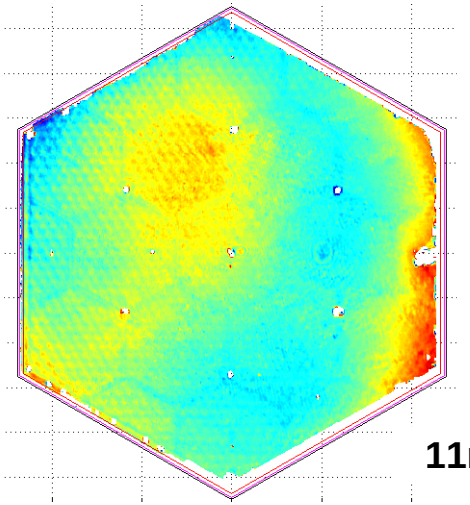
Figure Change Over the Operational Temperatures

- Operational temperature is 30K to 65K based on latest NGST analysis of JWST
- Change over this temperature change is about 20nm RMS
- Quilting does not change significantly over the operating temperature

TAKE PICTURES. FURTHER.

Figure Change Over Operational Temperature Range

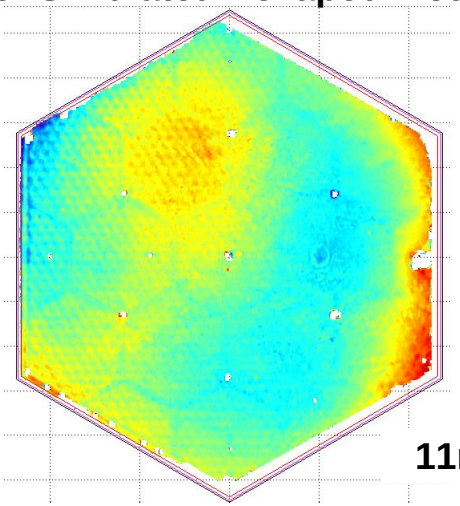
Raw Data



Vac/45-Vac/55

11nm RMS

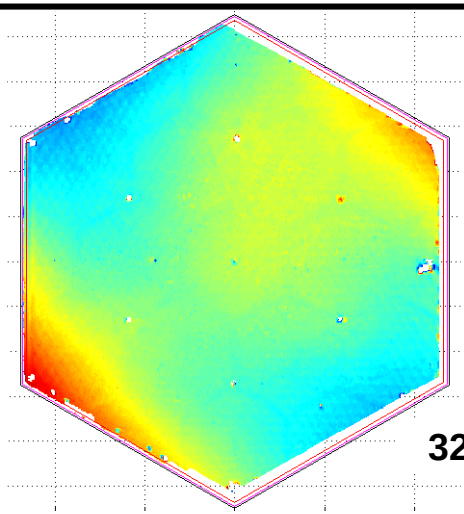
After Simulated Hexapod Motion



Relative Motion (mm)

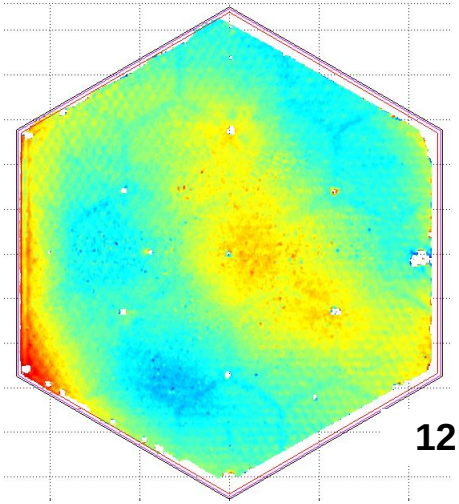
X: 0.0
Y: 0.0

11nm RMS



Vac/30-Vac/45

32nm RMS



X: 0.0
Y: -0.30

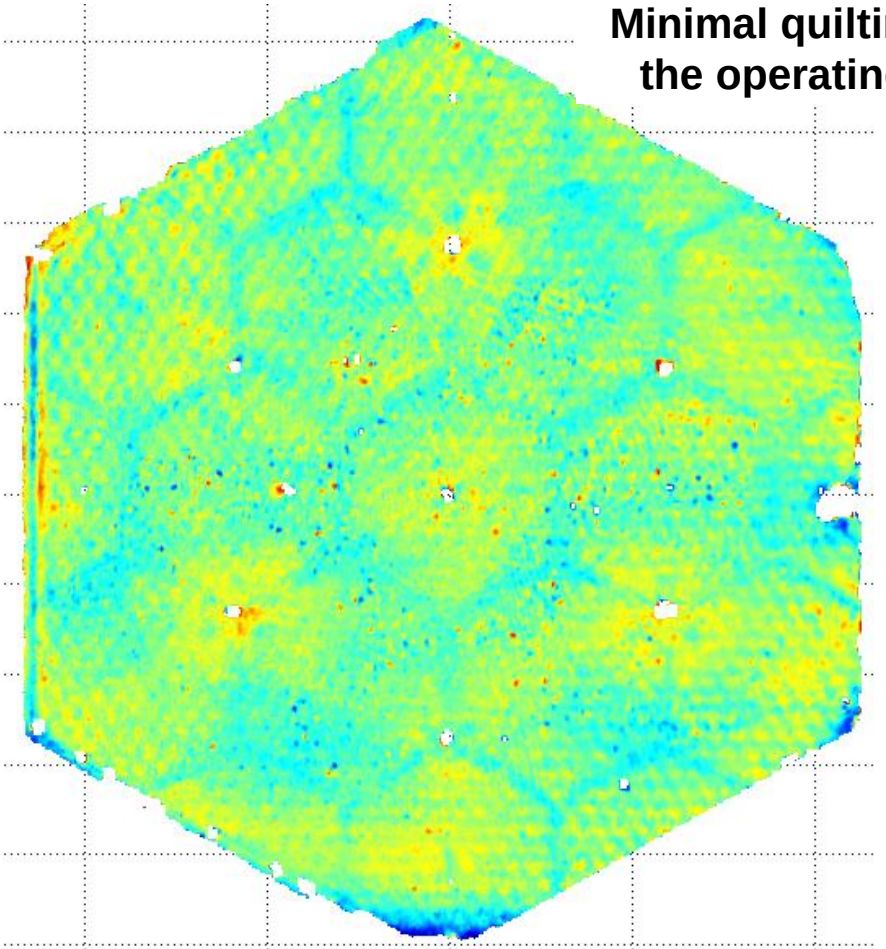
12nm RMS

Temperature gradient effects not backed out

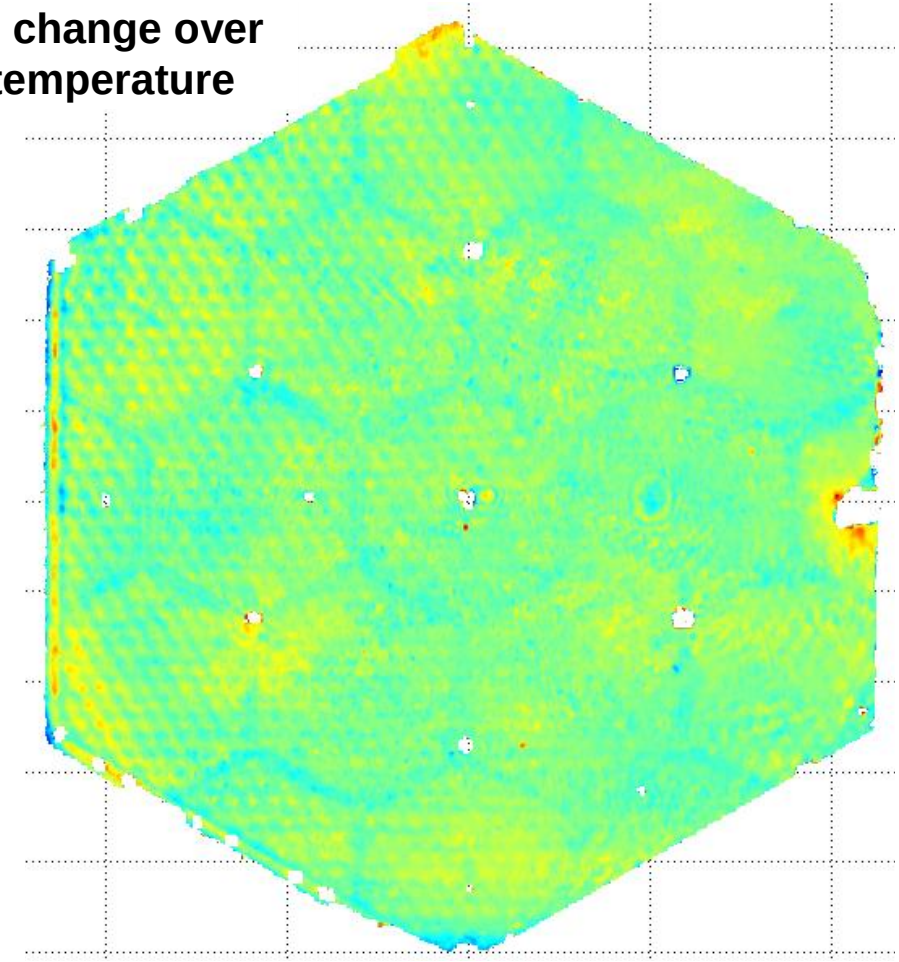
TAKE PICTURES. FURTHER.

Change in High Spatial Frequency Errors over Operational Temperature Range

Minimal quilting change over the operating temperature



30K – 45K
4.1nm RMS



45K – 55K
4.5nm RMS

Data Masked, Fringe Zernikes & Spurious Points (<1% Area) Removed

TAKE PICTURES. FURTHER.

Conclusions

- **Bulk temperature surface deformation is larger than expected**
  - Cause is under investigation by Kodak and Corning
    - Expect to be able to quantify the flight performance
  - Global figure is repeatable and can be null figured into mirror
  - Based on AMSD performance, PSD specification may be slightly higher than JWST specification
- **Thermal sensitivity over operating temperature indicates a similar phenomenon but is small enough to be acceptable**
  - Longer radius of curvature and stiffer mirror reduces impact for JWST

TAKE PICTURES. FURTHER.

Special Thanks

- **Special thanks goes to the XRCF team at MSFC and UAH**
  - Jeff Kegley, Phil Stahl, Kevin Russell, Ron Eng, Harlan Haight, Barry Hale, Richard Siler, Greg St. John, Ernie Wright, Harry Rutledge, John Tucker, Ken Whitley, Bill Hogue
  - James Hadaway, Pat Reardon, Ted Rogers

- **and finally, as Jeff Kegley so aptly put it at the end of the cryo testing as the mirror was leaving in the Kodak truck after 3 months of testing**

...what a long, strange trip it's been

Jerry Garcia